NOTES ON THE CLIMATE OF PERTH, WESTERN AUSTRALIA

By J. GENTILLI
Department of Geography, University of Western Australia, Nedlands 6009

CLIMATIC DATA FOR THE NATURALIST

An extraordinary variety of climatic data may be required by the naturalist, ranging from the extreme generalisation ("Perth has a mediterranean climate...") to the extreme topicality ("... inside the termites' corridors relative humidity nears 100%..."). Some excellent general climatic in-formation is readily available in print (e.g. Cooke 1901, Hunt 1929, Bureau of Meteorology 1966, 1969, 1975) or more recently from the beginning of observations at each station on microfiche and printout (National Climate Centre, n.d.), but the naturalist must select and adapt what is most relevant to his observations.

The *time factor* may be very important. Mean or total monthly climatic data are quite useful, but organisms go through diurnal cycles of activity and rest. For instance, monthly mean daily maximum and minimum tem-peratures give the monthly mean daily range, but with still and cloudy winter weather the range may be as low as 2°C and with clear summer weather with easterly wind as high as 20°C. Ideally the naturalist would install a properly exposed clockwork hygrothermo-graph or, better, a similar electronic recording instrument as close to the observation site as possible. Dew, although occasionally reported, is not measured consistently and records are not available; in any case, a brief period of sunshine would soon evaporate it. At Perth it can be a significant source of moisture in spring and autumn nights, and naturalists would have to make their own observations, with *ad hoc* instruments and pre-dawn inspections.

Duration time may be of vital significance, especially in the case of adverse conditions such as extreme heat or drought. Daily observations are particularly needed during heat waves which might otherwise remain hidden in the monthly records. The duration of drought should also be counted in days rather than months, because a month in which a drought was effectively broken in the last few days might not appear as having had a drought at all.

There have always been climatic trends, variations, oscillations and cycles. Some of them have been detected in the climate of Perth, and will be discussed later.

CONTINUA AND QUANTA, STEPS AND THRESHOLDS

Heat, measured in practice as temperature, is a *continuum*, i.e. there are no spatial or temporal gaps in its variations. Rainfall, on the other hand, is a discontinuous (discrete) phenomenon which varies by *quanta*: level ground under a rain cloud may get soaked while adjoining ground remains dry (but sloping ground is likely to cause surface and ground water to flow across the boundary). The uplift of a moist airstream increases the chances of rain, a downdraught in the lee of a hill decreases it. Mobile organisms are not likely to be affected, but plants are, and smaller and ephemeral plants particularly so. The effects of topography were taken into account in the preparation of Fig. 2.

A temperature record, while continuous, usually presents a succession of *steps* caused by the succession of daily heating and nightly cooling. In biological field observations it may be difficult to determine how much nocturnal inactivity is due to absence of light or loss of heat, or simply to the need for rest.

All organisms are governed by *thresholds*, minimum or maximum limits for survival or for normal or optimal activity. The most quoted threshold, 0°C (freezing point) is seldom reached in Perth, and only at ground level and for a few hours. European botanists used to consider 6°C as a threshold for good plant growth; at Perth this temperature is reached on a few winter nights within the screen, but grass temperatures recorded between 1899 and 1926 showed that the lowest minimum in each month was below 0°C from late May to early November and the average monthly minimum was below 0°C 4% of the nights in May, 21% in June, 46% in July, 50% in August, 21% in September and 4% in October. Plants, relatively dormant in winter, are more active in September than in June because of the warmer and longer September days.

Temperatures above 38°C are at least inconvenient to warm-blooded animals, and temperatures above 40°C actually injure some plant tissues, but in Perth they do not last long enough to injure animals, who find suitable shelter.

THE QUALITY OF OBSERVATION SITES

The site of observation is a very small sample of the locality where it is situated, and must be chosen with regard to its most important characteristics: aptness, representativeness and (for special studies) relevance to the subject or purpose of the study.

Aptness is decided by the laws of physics: barometers may be indoors, but thermometers for standard observations must be in a well ventilated preferably louvred box (usually a Stevenson screen) in an open space, preferably grassed, 1.25 m above ground. Rain gauges are high enough from the ground to avoid splashes, and well away from any obstruction. Evaporation measurements are more controversial. Wind observations are officially made 10 m above ground to avoid ground friction and turbulence caused by trees, buildings, etc., but this requirement results in readings which are too high for anyone studying insect life near the ground, or flowers, while being very significant in the study of higher-flying insects or pollen dispersal. Whole handbooks have been written about standard instrument exposure.

Representativeness simply means that the site's records must not be very different from those that would be got from a fairly large area around the site itself, ideally half way to the nearest recording site. In flat uniform country this is easily achieved, but in hilly landscapes or near bodies of water there arise various problems that may force a considerable degree of com-promise. A rain gauge situated upwind or downwind of even a small hill or a sand dune may give accurate but very unrepresentative readings. It is up to the naturalist to make allowance for such problems, which are the very essence of topoclimatic studies.

Unfortunately the most apt and representative records may not suit the needs of the naturalist. We are here in the realm of microclimatology: the unlined tunnel of the earthworm, the lined tunnels of the termites, the vertical and horizontal shafts of ants' nests, the humid air above a stream frequented by dragonflies, the rock or wall where the lizard suns itself, the shade where the kangaroo rests at noon, all require minute and accurate measure-ments made possible by modern instrumentation.

THE SITES CALLED PERTH

Official Perth weather and climate observations were made at various sites in the past, but until 1990 always within the present city limits. Differences between sites affect the records, particularly with regard to pressure and temperature (for which corrections are relatively regular and easy) and wind and rainfall (which are affected far less regularly and are more difficult to compare for different sites). The growth of trees or the erection of new buildings can drastically change the quality of a site and the representativeness of observations. The kind of records assembled in the 18th century was influenced by the point of view prevailing at the time: relevance to health at the beginning, atmospheric physics most of the time, agriculture in the second half of the century. In the second half of the 19th century environmental aspects of climate received more attention, and lately air pollution and air quality were measured, thus returning to the emphasis on relevance to health of nearly two centuries ago.

On the way to Western Australia, in 1829, Governor Stirling gave orders to the Colonial Surgeon "to keep a Journal of the weather and height of the Thermometer and a detail of every circumstance in the weather affecting health". Such records were kept at both the Surveyor-General's office and the

Colonial Surgery at Perth; the former series runs almost continuously from April 1830 to the end of 1876 and is available in manuscript form, but only fragments of the latter from 1842 and 1843 have been found. Both series recorded temperature, pressure, wind direction and state of the weather twice a day. There is no description of the site and exposure of the instruments. Similar records were kept inside a Perth house in 1830–31 and under a thatched hut throughout 1831. The exposure of the instruments was not often considered critical at the time, as long as direct solar radiation was avoided. The time of observations could even vary according to circumstances.

The *Inquirer* newspaper published weekly weather reports from the Surveyor-General's office (then near the crossing of Barrack Street and St George's Terrace, at about 16 m above sea level) from April 1840 to April 1845 and monthly ones from June 1845 to September 1846. In 1843 the *Journal of the Agricultural and Horticultural Society of Western Australia* (vol. 1, pp. 16–28) published pressure, wind and temperature data taken daily at 16 hours at the Surveyor-General's office, with the monthly number of rainy days. From May 1842 to May 1843 it also published wet and dry bulb temperatures obtained from Government House, a short distance eastwards along St George's Terrace. Rainfall as such was still neglected: the oldest quantitative records of rain were obtained at the Fremantle Signal Station from July 1852 to March 1859.

In 1876 a Meteorological Branch was created within the Surveyor-General's Department; observa-tions were made regularly at 0700 and 1200 hours. It is possible that the rain gauge may have been placed in a less obstructed space at the Botanical Gardens (now Government Gardens). In 1885 all instruments were transferred there, at about 11.5 m above sea level, and the times of reading were changed to 900 and 1500 hours. The number of days with rain was not recorded again until 1907. About 1924 the instruments were moved to a site less than 2 m above sea level, south of the Supreme Court building (which must have considerably

Table 1. Sites of official Perth weather observations

Period	Location	alt.m	km from sea
before 1876	Surveyor-General's Dept	c16	9.5
1876–1924	Government Gardens	11.5	9.5
1924–1930	" "	c2	9.5
1897–1967	Observatory (W.Perth)	c60	8.5
1967–1992	Regional Office (East Perth)	18.6	11.3
1993–	Aut.Weather Stn (Mt Lawley)	24.9	12
1944–1984	Airport (Guildford)	18	21
1985–June'91	" (")	12	21
July 1991–	" (Belmont)	29	21

affected earlier records), where they remained until the station was closed down in 1930.

In 1896 an astronomical observatory was built on Mt Eliza and the Government Astronomer was placed in charge of meteorological observations, which began on an adjoining grassed site, at 60 m above sea level, and continued until 1963. From 1963 to 1967 to reduce interference from new buildings, instruments were moved to a small plot of lawn near by, east of the old Hale School building. As will be shown later, the climate of the Mt Eliza sites differs significantly from those of all other Perth sites because of the greater height and more open exposure to the westerly winds. Fortunately records at Government Gardens and Mt Eliza overlapped from 1897 to 1927, so that a comparison could be made. In 1908 weather observations, at the same sites, were placed under the control of the new Commonwealth Bureau of eteorology.

In 1967 the new Regional Office of the Bureau of Meteorology opened near the corner of Wellington and East streets, east of the city, and the instruments were moved there; the site, at 18.6 m above sea level, was almost surrounded by tall buildings, particularly on the windward side, and was therefore quite unrepre-sentative. However, observations continued until April 1992. The Regional Office then moved to West Perth, without a site for observations, and records and forecasts were based on the International Airport. In November 1993 the Bureau was able to install an automatic weather station on a good, open site at about 24.9 m above sea level in Mount Lawley (City of Stirling), and official Regional Office records were resumed.

It is now a convention that weather observations for international requirements be made at airports; records at Perth Airport (Guildford) began in 1944, and were variously listed under Perth, Perth Airport, Guildford, and, after a small change of location about 1990, Belmont (National Oceanic and Atmospheric Administration, 1947–).

SITE AND TEMPERATURE

Differences in temperature between microclimates are far more important to living organisms than differences between meteorological sites. The best course to follow is to quote the relevant official temperature reading at the nearest station in order to establish a comparable base, and at the same time measure the actual temperatures in the relevant

microclimate. Also, while the official temperature is read at the prescribed regular intervals, it is nearly always desirable to record actual microclimate temperatures as often as possible, preferably continuously by means of a recording instrument. The heat of the day affects most animals, which usually if warm-blooded seek a shady spot to rest in the hottest hours and if cold-blooded have to seek heat in order to become more active. Even a passing cloud may reduce the temperature enough to affect the activities of some insects.

Table 2 assembles published and unpublished data to facilitate

Table 2. Mean monthly temperatures at the main observation sites (°C)

Mth	Period 1897–1926				Period 1945–59				Period 1973–87			
	Gard	Obs.	diff.	/100m	Obs.	Airp.	diff.	/10km	EPth	Airp.	diff.	/10km
Jan.	23.8	23.2	.6	1.00	23.7	23.6	.1	.08	24.8	24.5	.3	.3
Feb.	23.7	23.3	.4	.67	24.1	24.0	.1	.08	25.2	24.9	.3	.31
Mar.	22.2	21.8	.4	.67	22.8	22.4	.4	.32	23.5	22.9	.6	.62
Apr.	19.4	19.2	.2	.33	19.3	18.7	.6	.48	20.2	19.4	.8	.82
May	16.0	15.9	.1	.17	16.1	15.5	.6	.48	17.0	16.0	1.0	.97
June	13.8	13.8	0	0	14.2	13.6	.6	.48	14.9	14.0	.9	.93
July	13.0	12.9	.1	.17	13.2	12.7	.5	.40	14.0	13.1	.9	.93
Aug.	13.6	13.3	.3	.50	13.5	13.0	.5	.40	14.4	13.4	1.0	.97
Sep.	15.0	14.6	.4	.67	14.7	14.2	.5	.40	15.7	14.6	1.1	1.13
Oct.	16.7	16.0	.7	1.17	16.1	15.6	.5	.40	17.5	16.5	1.0	.97
Nov.	19.7	19.0	.7	1.17	18.7	18.3	.4	.32	20.0	19.2	.8	.82
Dec.	22.1	21.4	.7	1.17	21.0	20.7	.3	.24	22.4	21.8	.6	.62
Year	18.3	17.9	.4	.67	18.1	17.7	.4	.32	19.1	18.3	.8	.82

Data sources: Hunt (1929) and R.Tapp (priv.comm.1994)

comparison between the successive sites of official observations. Height above sea level is the most significant difference between Government Gardens and the Observatory, but the usual lapse rate of 0.55 to 0.6°C per 100 metres is mostly found before the equinoxes and in the annual means. It falls to zero about the winter solstice, and rapidly rises to double the usual rate in late spring and early summer, until the summer solstice.

The likely explanation of these differences is the absorption and storage of the increasing springtime heat at the low and sheltered Government Gardens site while strengthening daily breezes and generally more open exposure to the wind helped disperse much of the heat from around the Observatory at the top of the hill.

Diurnal variations result in a higher lapse rate in the daytime, with mean maximum temperatures being 0.5 or 0.6°C higher at the Gardens than at the Observatory during May to July, rising to be over 2°C hotter in November. Mean minimum temperatures have a negative lapse rate, the Observatory being slightly warmer than the Gardens throughout the year, or about equally warm at the equinoxes. Downhill drift of cool air from the higner ground, stagnation of the cool night air and later sunrise because of their location contribute to the lower minima at the Gardens during the cooler season.

In a comparison of records at other sites with those at the Airport differences in height become less significant than distance from the sea, and in Table 2 average temperature differences have been shown as observed and also reduced to a standard 10 km difference in distance from the sea. Generally, the Airport is cooler than the other sites, but only very slightly so in the summer, contrary to what was noticed in the Gardens-Observatory comparison. Differences become more noticeable in the winter, partly because of drainage of cool air from the scarp to the foothills and partly because of the loss of night radiation from the large bare areas of the airport. The peak of thermal difference between East Perth and the Aiport is reached at the equinoxes, particularly in the spring.

The essential thermal differences between the various sites are perhaps best expressed by the mean *daily range* of temperature, shown in Table 3. One is tempted to say that even the few kilometres further away from the coast are enough to give the Airport a more continental climate than at any other site. Differences between the other sites are very small, but possibly the East Perth site, with its relatively moderate temperature range even in summer, may be viewed as the least representative one for the Perth natural environment.

SITE AND RAINFALL

Rainfall is usually recorded for the 24 hours beginning at 0900 each day, and this means that any rain fallen between midnight and 0900 is credited to the previous day. When summer time is in force, it should be made clear whether allowance is made for it or not. When comparing monthly totals, a correction may be needed for the unequal number of days in the various months.

Rainfall may be shown as a *total* amount (as the depth of water caught in the rain gauge or pluviometer), a *frequency* (usually the number of days with rain) or an *intensity* (usually the amount fallen in each day with rain, or in shorter periods, even within 15 minutes in

Table 3. Daily range of temperature at the main observation sites (°C)

Month	Gardens 1897–1926	Observ. 1945–59	E Perth 1973–87	Airport 1945–59	Airport 1973–87
Jan.	12.9	12.2	11.6	15.1	15.1
Feb.	13.0	12.2	11.4	14.5	14.5
Mar.	12.3	11.9	11.1	14.4	14.0
Apr.	11.7	10.8	10.0	13.2	12.5
May	9.9	9.2	9.1	11.4	11.0
June	8.9	8.1	8.5	10.0	9.6
July	9.1	8.3	8.4	9.9	9.5
Aug.	9.5	9.1	8.9	10.8	10.0
Sep.	9.7	10.0	9.5	12.0	11.2
Oct.	10.2	10.4	9.8	12.6	12.1
Nov.	11.6	11.0	9.8	13.5	12.9
Dec.	12.1	11.4	10.2	14.2	14.0
Year	*10.9*	*10.4*	9.8	*12.6*	*12.2*

Data sources: Hunt (1929) and R.Tapp (priv.comm. 1994)

Table 4. Mean total rainfall (mm) and number of rain days

Mth	Gardens		Observatory				E.Perth		Airport			
	1907–29		1907–29		1945–59		1973–87		1945–59		1973–87	
	mm	days	mm	days	mm	days	mm	days	mm	days	mm	days
Jan.	9.8	3.1	9.5	3.4	4.9	2.7	11.1	2.3	3.9	2.4	8.5	2.2
Feb.	13.2	2.8	14.4	3.1	18.3	2.4	18.4	2.9	13.8	2.2	17.1	3.1
Mar.	18.9	4.7	20.1	4.9	13.9	3.2	10.1	3.9	11.2	3.2	11.2	3.6
Apr.	34.4	6.7	38.0	7.0	52.3	8.6	40.1	7.3	43.8	7.9	40.3	7.4
May	130.6	14.7	136.3	15.0	125.1	14.2	111.3	13.3	114.0	14.3	101.7	13.2
June	183.6	17.5	190.9	17.6	211.5	17.8	162.6	16.3	199.0	17.9	148.8	16.2
July	179.6	18.3	185.2	18.9	193.5	19.9	170.4	17.6	170.9	18.3	157.5	17.2
Aug.	140.1	18.0	148.4	18.7	132.0	16.5	116.5	16.0	131.6	16.0	112.4	15.7
Sep.	88.6	14.5	90.7	15.8	61.7	12.5	73.3	12.1	62.9	12.8	68.2	11.9
Oct.	56.8	12.4	60.8	13.4	60.1	12.0	47.6	9.2	56.6	11.7	38.5	8.9
Nov.	18.9	6.6	20.7	7.3	30.5	7.7	25.6	7.4	29.5	8.2	28.4	6.8
Dec.	12.9	4.0	13.1	4.8	18.0	4.5	9.2	4.0	15.2	4.9	7.6	3.7
Year	887.4	123.4	930.7	129.6	921.8	122.2	796.4	112.3	852.4	119.8	740.1	110.1

special cases). Until 1973 a day with at least 1 point of rain (1/100 of an inch, or 0.25 mm) was counted as a rain day or, loosely, a wet day. With the conversion to the metric system, from 1974 onwards a day had to record 0.5 mm to be credited with rain, and days with less than 0.5 mm are recorded as having had only traces of rain.

A comparison of rainfall records between the same sites as in the preceding tables is shown in Table 4. The earlier years are omitted, because until 1907 no record was kept of the number of days with rain. Different sites may be compared only over the same period of obervations, i.e. Gardens and Observatory for 1907–29, Observatory and Airport for 1945–59, East Perth and Airport for 1973–87. No reliable comparison may be made between Observatory and East Perth data because there was only a very short overlap in the operation of both sites

Summer rainfall is very variable in time and irregular in its spatial distribution. More may fall at the Airport than at other sites because of the greater instability of the air near the Darling Scarp. The more reliable and much more plentiful May and winter rains were about 5% higher at the Observatory than at the Gardens and, in a later period, some 10% lower at the Airport than at the Observatory. In a study of rainfall in successive days Swindell (1979) found that distance from the sea was about twice as significant as altitude and aspect. On the average, during a few days, rainfall on the coastal plain decreased 0.15 mm/km away from the coast, a rate close to the 10% difference between East Perth and the Airport.

These differences are particularly significant at Perth because its normal rainfall is just sufficient to support a forest, as opposed to an open woodland such as is formed by Wandoo. A rainfall below average immediately imposes some stress on the vegetation, as shown for instance by Havel (1979).

A RAINFALL MAP OF PERTH

A metropolitan area measuring some 65 km from north to south and over 35 from west to east, and rising from sea level to over 400 m on its eastern margin, must show some areal variations in its climate. The altitudinal gradient varies from 0°C per 100 m in June to nearly 1.20 in October to December (Table 2). Distance from the sea accounts for little less than 1°C from May to August, rising to just over 1°C at the spring equinox. It is much less, 0.3°C or so, during most of the summer. Given a contoured map and using the ranges of temperature shown in Table 3 the preparation of a map of average temperatures in the Perth Metropoltan Area becomes relatively easy.

Rainfall is more difficult to estimate because it is affected by more factors and can vary substantially over a small area. On the other hand, at different times rainfall was recorded at over 90 sites in the present metropolitan area. Careful comparison of the physical attributes of the various sites and their recorded observations allows some plausible estimate for the intervening points.

Figure 1 shows the altitude and annual rainfall of the stations near the Darling Scarp. The solid line shows the average correlation between altitude and rainfall, at a rate of very nearly 1 mm per 100 m. The 865 mm in the equation would be the mean annual rainfall of a station at sea level.

Stations near dam or weir sites are shown by small circles and were excluded from the calculations because their rainfall was much higher than would have been expected, as is shown by the broken line: 2.1 mm per100m, more than double the normal rate. The explanation is simple: the recording sites are near the dam sites, near the valley floor or at most at the top of the dam, while the surrounding land, and particularly that at the back of the reservoir, rises much higher, to 400 or even 500 metres at some points. The funnelling of the westerly wind up the valleys can also increase the rainfall by increasing the thickness of the airstream.

An earlier analysis of the rainfall near the Scarp (Gentilli 1979a) showed that the Scarp has no effect on the number of rain days, but the intensity of the rain increases noticeably from near the foot of the Scarp to a short distance beyond the top. If the uplift of the airstream were the main cause of the increased rainfall there should be some increase in the number of rain days. The substantial and sudden increase in the intensity of the rain suggests that there is a more dynamic cause: the warm water of the longshore Leeuwin Current adds some moisture, warmth and instability to the westerly airstreams, and the sudden rise against the Scarp acts more like a trigger on an unstable airflow than as an incline under a steady airstream. Having lost a substantial part of its additional vapour over the Scarp, the air returns to its previous

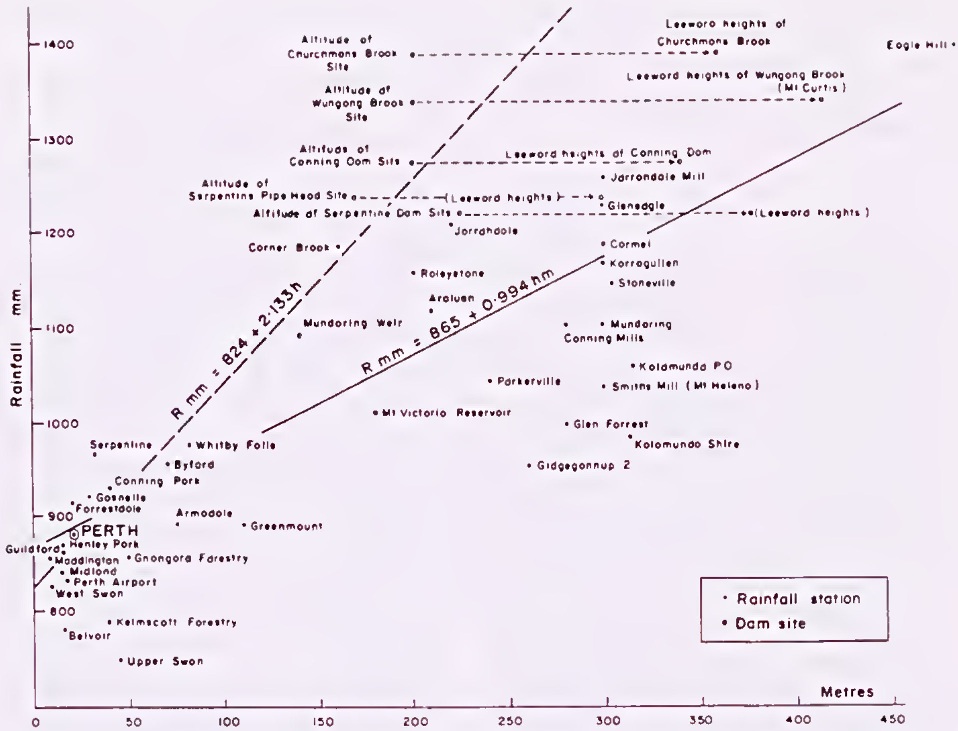

Figure 1. Altitude and mean yearly rainfall of stations near the Darling Scarp. The dashed line shows that the rainfall increases by an average of 2.133 mm for every metre of altitude. If, however, the calculation is based on the altitude of the heights to the leeward of dam sites, the rate of increase, as shown by the continuous line, drops to 0.994 mm per metre.

characteristics as it proceeds further inland.

A rainfall map of the Perth Metropolitan Area was published by the Bureau of Meteorology (1969, p. 81) but the interval of 5 inches (127 mm) between isohyets made it too general as a basis for further work. The interval was reduced to 2 inches (50.8 mm) near the coast and in the Swan Valley, but not enough account was taken of the dune topography, which is now mapped in considerable detail (DOLA 1972–). Figure 2 has taken into account these various factors and could be used by naturalists to estimate the average annual rainfall of any locality within its scope.

Rainfall is lower in the middle Swan Valley than further south because the Darling Scarp is slightly lower and displaced towards the east. The Kalamunda Spur extends further westwards and rises steeply, forcing the airstreams to climb. Besides altitude, the effect of latitude cannot be neglected; The highest average yearly falls reach 1271 mm at Canning Dam and 1337 mm at the Wungong Dam. Figure 2 shows the initials or first two or three letters of the names of stations, with the respective yearly totals, and the isohyets have been drawn taking detailed account of the topography. Isopleths over the sea and around the Cockburn Lakes, for which there are no records, are shown by dashed lines; it is surmised that the coastal dunes further west shelter the shallow depression where the lakes are enough to keep the rainfall below 850 mm per year.

GAUGE RAINFALL AND ACTUAL WATER AVAILABLE

The rainfall gauge intercepts raindrops before they reach the ground. Any obstacle in their path affects raindrops, according to the angle of impact, resulting in sideways splashing, or coalescence of small drops to form heavier ones, or continuous deflection of many drops to form a trickle, or delay or temporary retention of raindrops in some way or other. Interception by tree canopies can be very important: Wandoo intercepts about 10% of the rain, Jarrah 20%, pines (and presumably casuarinas) 30%, more if the rainfall is heavy . Light rain may totally fail to reach the ground under pine trees, and the ground may begin to dry a month or two earlier under them (data generalised from Burrows, 1987). The implications of this for small ground-living animals and plants may be very important. The naturalist may have to use makeshift gauges to measure the actual rainfall under the plant canopy, or at least will have to calculate the throughfall by subtracting the presumed interception from the gauge readings.

Conversely, the amount of water available to deep-rooted plants will be more than the gauged rainfall when the roots meet the watertable, which reaches its highest point around October every

Table 5. Rainfall intensity (mm/day)

Month	Gardens	Observatory		E.Perth	Airport	
	1907–29	1907–29	1945–59	1973–87	1945–59	1973–87
Jan.	3.2	2.8	1.8	4.8	1.6	3.9
Feb.	4.7	4.7	7.6	6.3	6.3	5.5
Mar.	4.0	4.1	4.3	2.6	3.5	3.1
Apr.	5.2	5.4	6.1	5.5	5.5	5.4
May	8.9	9.1	8.8	8.4	8.0	7.7
June	10.5	10.8	11.9	10.0	11.1	9.2
July	9.8	9.8	9.7	9.7	9.3	9.2
Aug.	7.8	8.0	8.0	7.3	8.2	7.2
Sep.	6.1	5.8	4.9	6.1	4.9	5.7
Oct.	4.6	4.5	5.0	5.2	4.8	4.3
Nov.	2.9	2.8	4.0	3.5	3.6	4.2
Dec.	3.2	2.8	4.0	2.3	3.1	2.1
Year	*7.2*	*7.2*	*7.5*	*7.1*	*7.1*	6.7

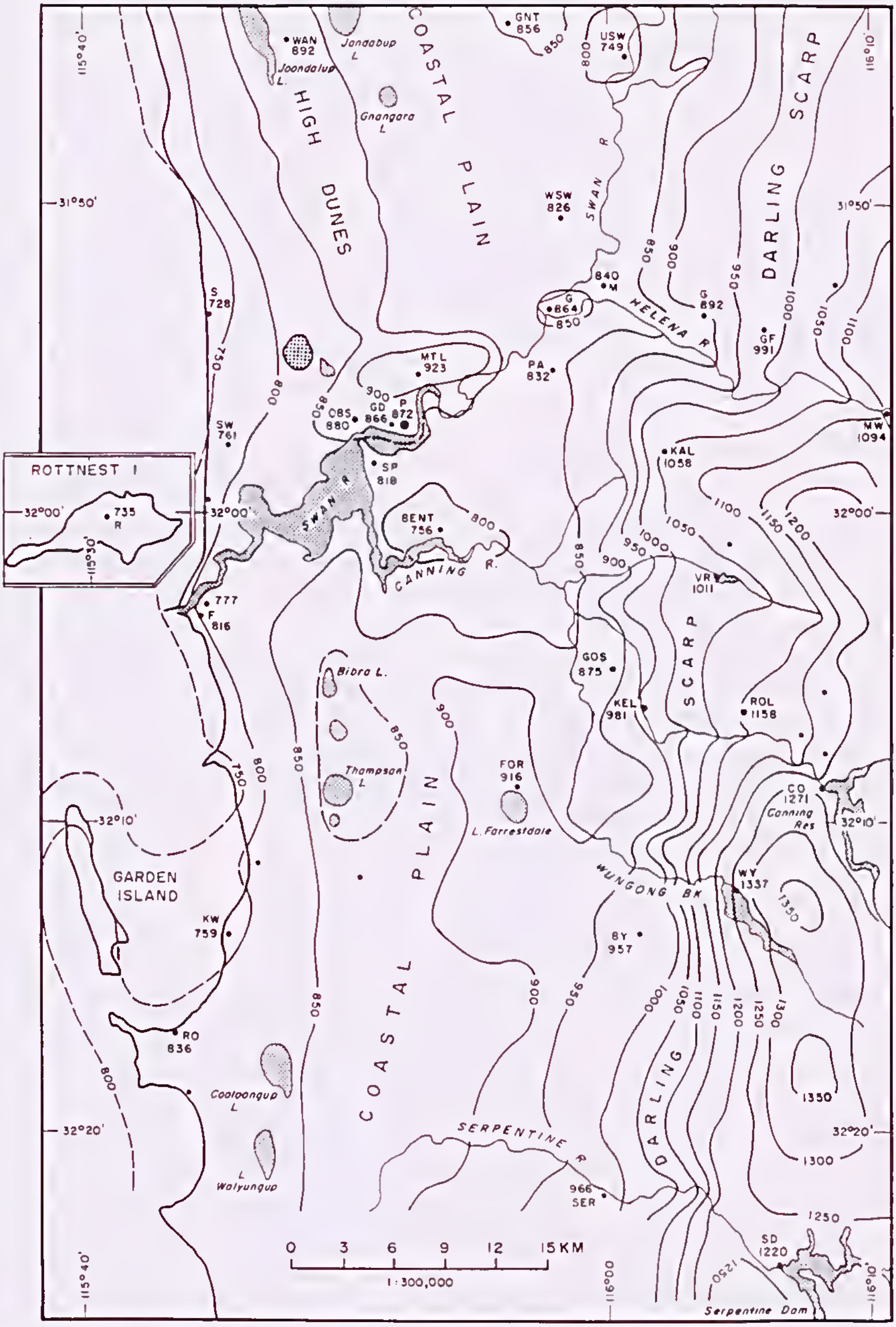

Figure 2. Mean annual rainfall of the Perth Metropolitan Area. Note the effect of topography.

year (see Figure 6 below).

On slopes, the gauged rainfall may be slightly greater near the top because of the sudden uplifting of the airstream, but the water flows rapidly downhill, so that the higher ground becomes drier sooner, while the lower slopes gather not only the direct rainfall, but also some of the runoff at the surface and immediately below. The relative size, density and foliage development of the plant cover usually reflect this trend even where the floristic composition remains the same.

OTHER RAINFALL DATA

Other very valuable data on Perth rainfall (with no distinction between Gardens and Observatory but covering separately Fremantle and Guildford town as well) are included in the 1969 Bureau of Meteorology's book. They include the yearly totals arranged in class intervals, monthly average and extreme values, percentage frequencies of monthly totals in specified ranges, highest daily rainfall on record. For Perth only there are tables showing the mean daily rainfall for each day of the year, mean number of days per month on which given amounts were received or exceeded, frequency of rain days (with at least 1 point and 10 points respectively), percentage probability of rain in any hour for each month, mean hourly rainfall for each month, monthly frequencies of occurrence of of consecutive rainless days and consecutive rain days. Other tables show the monthly frequency of rainfall in given ranges with wind from given directions. The maximum rainfall intensity recorded at Perth during

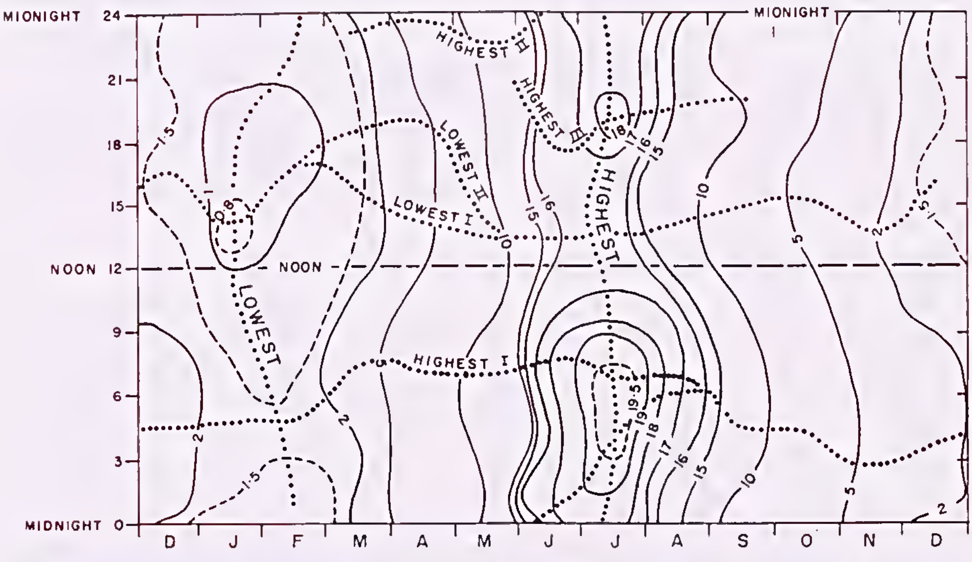

Figure 3. Mean 3-hourly (larger type) and monthly (smaller type) rainfall at Perth. Notice how several months have more than one average time of highest or lowest falls.

specified periods ranging from 5 minutes to 3 days is also shown with the respective dates, and the estimated recurrence from once in 1 year to once in 45 years is shown on a graph.

The probability of rain in any single hour in each month of the year, as published, was too detailed for practical purposes, and Figure 3 has been prepared for 3-hourly periods. The dotted lines show the times of highest and lowest average falls in 3 hours (vertical scale at the left, small writing along more or less horizontal lines) and in the year (months shown at the bottom, near-vertical lines, larger writing). The 3-hourly totals do not vary very much, and various peaks (highest I,II,III) and troughs (lowest I and II) can be seen, which may also vary considerably from year to year. There is, however, a general pattern that can be detected, especially the pre-dawn and after-sunset maxima in the winter months, and the early-afternoon minimum at mid-summer.

FREQUENCY OF GIVEN AMOUNTS OF RAIN

Extreme seasonal differences in the amount of rain received are one of the main features of the Perth climate, in fact much more so than in the Mediterranean regions from which the dry-summer climate takes its name. Tables 4 and 5 and Figure 4 are very valid representations of these seasonal differences in rainfall, but they are based on averages. Some comparison must also be made for the actual amounts received.

Table 6 shows the amounts of rain received in each month over 100 years, i.e. 1200 monthly amounts as they actually happened. Any month from November to April may be rainless, but this happened only once in November and three times each in March and April. Any

Table 6. Frequency of monthly rainfall of given amounts, 1891–1990.

Month	0 or traces	1–25	26–50	51–100	101–150	151–200	201–300	over300
Jan.	10	84	4	1	1	–	–	–
Feb.	16	70	11	2	–	1	–	–
Mar.	3	71	18	6	2	–	–	–
Apr.	3	31	26	34	6	–	–	–
May	–	3	9	27	31	23	7	–
June	–	–	–	13	19	30	35	3
July	–	–	–	10	24	41	21	4
Aug.	–	2	2	29	37	19	9	2
Sep.	–	4	19	49	22	6	–	–
Oct.	–	10	39	42	9	–	–	–
Nov.	1	68	26	5	–	–	–	–
Dec.	5	79	15	1	–	–	–	–
Year	501–600	601–700	701–800	801–900	901–1000	1001–1100	1101–1200	over 1200
	4	12	18	24	21	12	7	2

month except June and July may get fron 1 to 25 mm of rain, but in fact this is quite rare in May and August to October.

A more positive aspect of climate is shown by the number of months receiving more than, say, 50 mm of rain, as happens from April to October, except that in April and October this involves about half the years on record, while from May to August it is nearly the general rule. Further groupings or separations of months by their rainfall frequencies shown in Table 6 may be left to the naturalist, according to the needs, tolerance or limits of the organisms studied. An interesting case is that of April, which is bimodal, i.e. has two maximum frequencies, 1 to 25 and 51 to 100 mm: any organism which feels the stress of the usually dry summer (or, in the Nyoongah calendar, *birok* and *burnuru* in succession) may be drastically or even catastrophically affected by a dry April.

Distribution of yearly total amounts is smoother, with a fairly steep rise from 4 years with 501 to 600 mm to 24 years with 801 to 900 mm and tapering off slowly with the rare 2 years with over 1200 mm.

PERTH'S SEASONS

Perth's Nyoongah (Nyunga) Aborigines divided the year into six seasons, according to the weather and environmental conditions, with particular regard to food supplies and, to some extent, shelter; the same season could vary slightly from year to year, and so some seasons could be of different length. By combining the information given by Berndt and Berndt (1979), Bindon and Walley (1992) and other sources one obtains Table 7. The equivalence to the two calendar months listed for each season is only approximate.

There seems to be no great climatic difference between *birok* and *burnuru*, save for occasional more humid days towards the end (in March). Reference to Table 2 shows that mean temperatures remain above 20°C from December to March. Temperatures decline rapidly in April–May, and average less than 14°C in June to August, the traditional winter. They rise gradually in September to November. This would give four thermal seasons, with a summer of four months and an autumn of two.

Rainfall records (Tables 4 and 5) show a driest period in December–January, and rare but more intense falls in February. March has less infrequent but also less intense falls. This shows a slight difference in rainfall regime between *birok* and *burnuru*. Rainfall increases rapidly in April–May and reaches its peak in June–July. August has definitely less rain but still as many rain days, with less intense falls. September rains are lighter and less frequent, and this month is more closely linked with October–November than with August. This would give a year with six seasons, with August as a pre-spring of its own, and September to November as a three-month spring.

A tabulation of many climatic data for Perth (Gentilli 1971, pp. 298–299) still does not help to separate September from October, but shows more difference between December–January (mean monthly evaporation over 240 mm) and February–

Table 7. Names, approximate timing and characteristics of Aboriginal seasons.

Season	Approx. timing	Usual weather	Food supplies
Birak or Birok	Dec., Jan.	Hot and dry, very high evaporation, afternoon breezes.	Seeds, lizards, snakes; no shelters needed; lakes dry, firing bulrushes.
Bunuru or Burnuru	Feb., March	Hot E and N winds, high evaporation.	Roots, zamia nuts, nectar; bush firing.
Djeran or Wanyarang	April, May	Cooler, SW winds, night dew, showers.	Shelters built, skin cloaks sewn.
Makuru or Maggoro	June, July	Cold and wet, westerly squalls.	New shoots, frogs' eggs.
Djilba or Yilba	Aug., Sept.	Less rainy, becoming warmer.	Roots, flowers; lakes deepening, frogs.
Kambarang	Oct., Nov.	Rains petering out, night dews, occasional hot days.	Plenty of eggs, young animals.

March (under 220 mm). The same criterion of mean monthly evaporation allows also to link August and September (monthly evaporation 60 to 90 mm per year). Once more, autumn (in May, with evaporation around 70 mm), is shorter than spring (August–September, 60–90 mm).

Evaporation is affected by several factors, the most important of which is solar radiation. The combination of solar radiation (from Spencer 1976) and rainfall shown in Figure 4 gives a clear separation of monthly climates and of seasons, be they Aboriginal or European.

The highest position of the sun in the sky and the longest duration of daylight are reached at the solstice, on December 21, and by the beginning of February both factors have decreased slightly but noticeably, while temperatures only follow with the usual lag of five or six weeks. Figure 4 shows the compactness (the evenness) of *birok* and summer and the better suitability of *burnuru* and *djeran* to distinguish the accelerated changes of autumn, which includes a March that is very often the tail end of summer rather than part of autumn itself. At the opposite time, *makuru* is a compact wet and dark season, whereas winter is unevenly extended by the inclusion of August, when rainfall may still be frequent but becomes noticeably lighter. The kink in October is due to a sharp increase in radiation intake because of the combination of more hours of daylight and

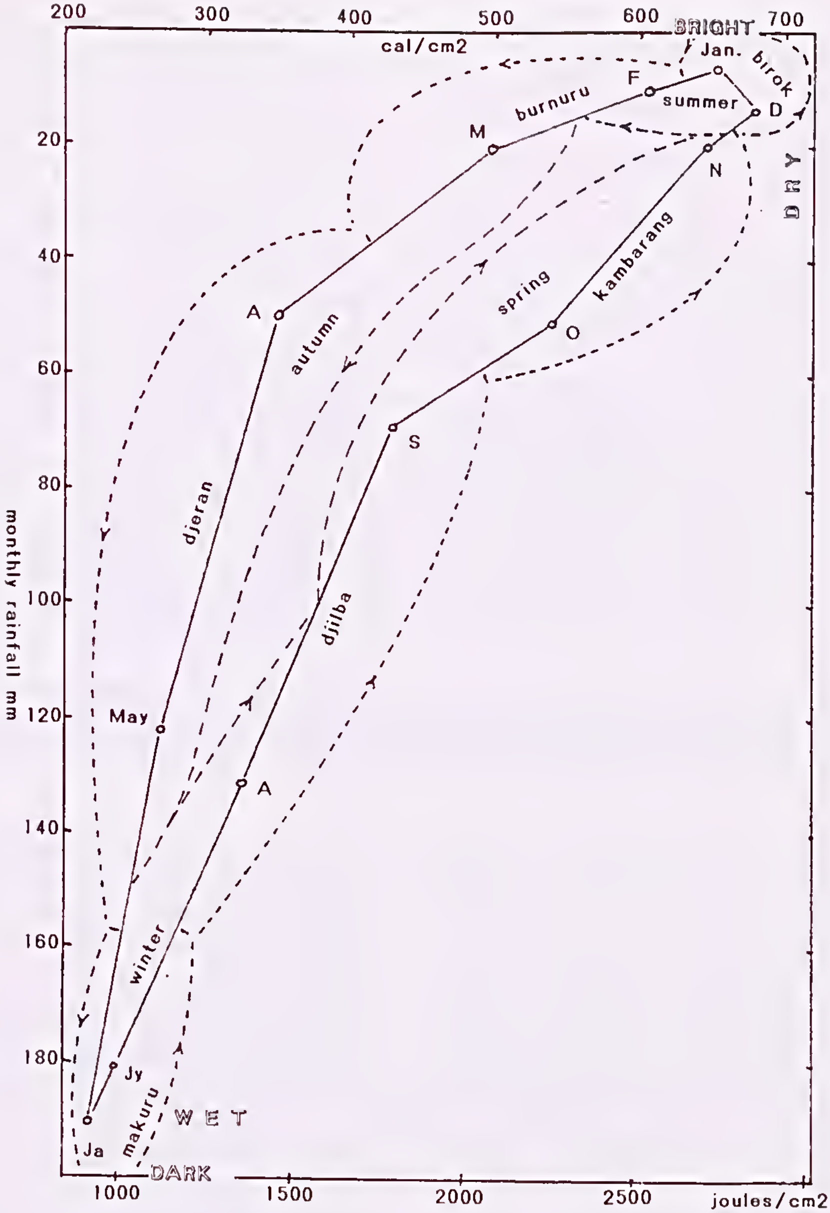

Figure 4. Monthly march of solar radiation and rainfall. Most months are shown by their initial, 2-monthly aboriginal seasons on the outside of the polygon and conventional 3-monthly seasons on the inside. Dashed lines show the seasons' approximate limits. Note the enormous differences in the rates of change between solstitial and equinoctial seasons.

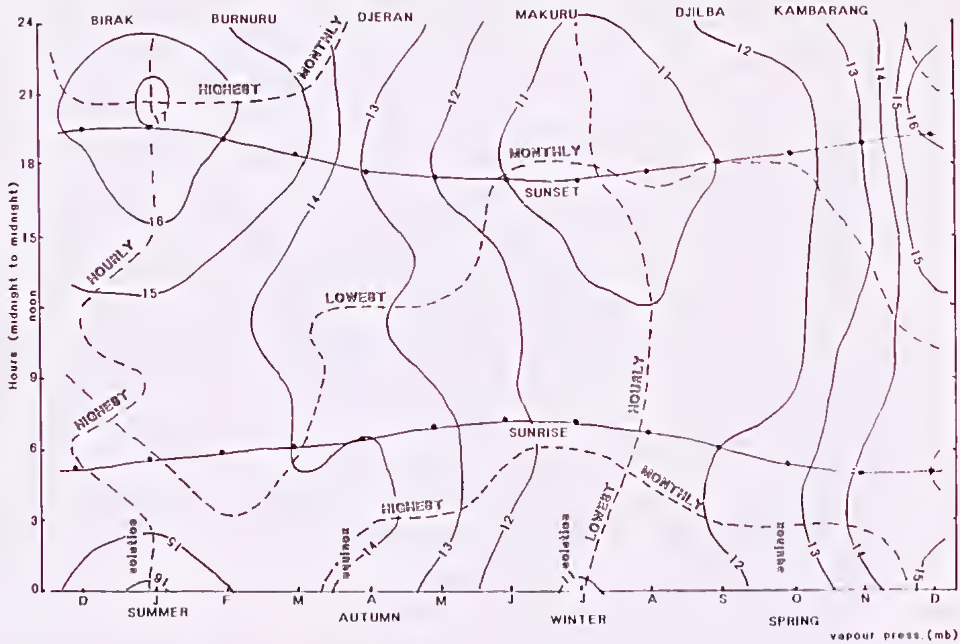

Figure 5. Hourly and monthly moisture in the air, shown as the pressure exerted by water vapour, in millibars. The highest moisture content occurs in summer afternoons and evenings, as the sea breeze brings in moisture from the ocean. The driest conditions are in the winter afternoons and evenings.

clearer sky. *Djilba* and *kambarang* are better and more even climatic subdivisions than August and spring of the European calendar.

Vapour pressure, whether expressed in millimetres of mercury or in millibars, is a very good expression of absolute humidity, which affects respiration and transpiration of organisms, Figure 5 shows the average hourly and seasonal changes in vapour pressure, expressed in millibars.

Fig. 5 is the best evidence of the fact that March belongs to the preceding season, be it *burnuru* or summer, rather than to the following season. From December to March inclusive, the most humid conditions occur from mid-afternoon to evening as a result of the cool sea-breeze which bring in moisture from the sea. By the end of March there is a sudden switch and the most humid conditions occur in the early morning, before the increased evaporation that follows sunrise. The times of lowest vapour pressure are to a great extent complementary, about sunrise in summer and March, about noon in *djeran* (April–May), and about sunset in *makuru* and *djilba* (winter and September). *Kambarang* (October–November) is the season in which the lowest humidity moves gradually from sunset to noon, while the highest humidity continues to occur before sunrise, before the advent of the hot times and the sea breezes which sweep in the extra moisture from the sea.

RAINFALL, GROUNDWATER AND LAKE LEVELS

Groundwater is recharged by rainfall and runoff. Groundwater is lost by evaporation, either directly or through the transpiration of plants. In the Perth area, away from the foothills, it may be assumed that rainfall recharges groundwater, after some lag which smoothes the process, at about the same rate, i.e. 1 mm of groundwater for every mm of rain, starting from the lowest post-summer level, usually in March . Depletion of the watertable occurs at the same rate, beginning from the highest post-winter level.

Since the lakes of Perth are the exposed part of the watertable, it follows that their level will vary accordingly, with the shallower ones becoming dry every summer, most of the others gradually reaching a lower level, contracting in area and exposing more and more dry shores, welcomed only by waders. Only through human action are there a few lakes kept at about the same level throughout the year. Lake Monger is the largest and best known of these. There are also a few small lakes that are kept as compensatory basins, best known among them the two Hyde Park lakes (Bekle and Gentilli, 1993, p. 454).

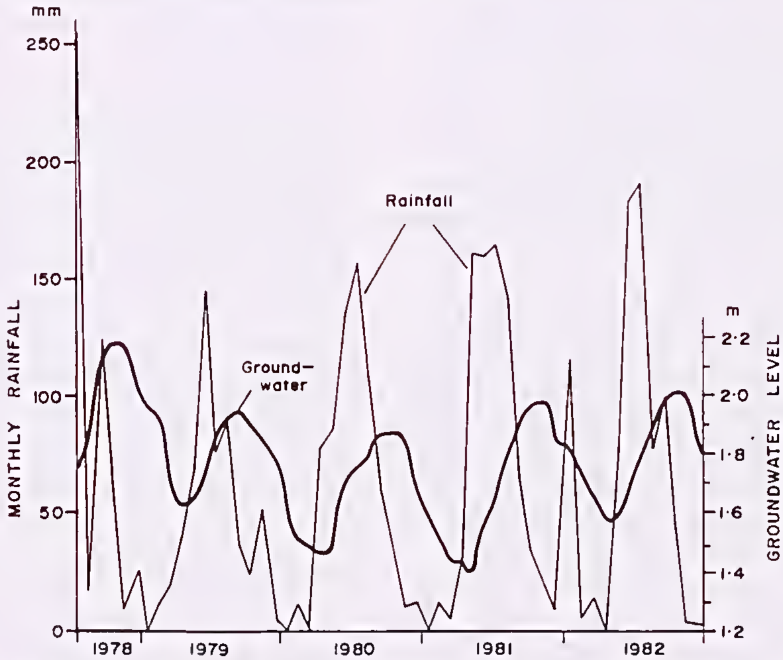

Figure 6. Rainfall and groundwater in 1978–82. There is a lag of several months between the rainfall and the recharge of groundwater, and the lighter falls may be lost through evaporation before they have any effect. *(By courtesy of Dr I.G. Eliot).*

THE WIND

Wind is a very important, yet often neglected, part of the climatic environment. Non-saturated air absorbs moisture until it reaches saturation, so not only does it cause evaporation from water surfaces, but also removes water from the surface of plant and animal bodies. Wind hastens this process as it blows past. In addition, wind exerts some pressure against exposed surfaces.

Wind data are available as tables of frequency and force from each main direction, wind roses, total wind run for 24 hours, and speed of strongest gust.

Perth has a very strong sea breeze (the "Fremantle Doctor") which blows roughly from forenoon to evening, initially almost from the south, veering to the west during the afternoon. It arises occasionally on clear warm days after the end of winter, and regularly later on, with its peak in summer. On very hot summer days with strong easterly winds it cannot arise, or at most dies down early and not far from the shore.

The sea breeze blows droplets of salt water over the shore, enough to prevent or weaken the growth of salt-sensitive plants. With a peak speed of 15–18 km/h, it causes some asymmetry in plant growth, making some shrubs and trees show poorer foliage on the upwind side, and better growth downwind.

It plays an important role in beach dynamics, steadily moving coastal waters and sand northwards; the greatest beach width is normally achieved after midsummer.

Westerly winds prevail in winter, with the strongest gales coming from the north-west. There are many factors that control the evolution of a shoreline, but the most basic controls are those of shape and orientation of the coast, and the angle of impact of the waves.

The shoreline at Quinns Rocks and Whitford was badly damaged in the winter of 1995. The trend of the shore and the long-term deposition of sand are shown in the excellent charts of coastal waters published by the former WA Department of Marine and Harbours in 1987. Figures 7.1 (Quinns Rocks shoreline) and 7.2 (Whitford shoreline), based on these charts, show some almost incredible similarities, first of all in the shape of the large areas between 5 and 10 metres deep (A).

The impact of nor'westerly blows (shown by the arrows) hits the shore at various angles; the nearer the angle to 90 degrees (head-on), the stronger the blow on the shore. The actual angle would be affected by the vicinity of obstacles such as reefs, banks, headlands etc., but the stronger the blow, the closer it is likely to be to the direction of the wind. The force of the wind increases far more than proportionally to its speed, and this is something that must be taken into account.

The impact of the waves on the shoreline removes large amounts of sand. The alignment of the coast just south of both the Quinns ramp and Whitford beach deflects much of this sand clockwise to form the sandbanks B. The breakers against the reefs at C cut the sandbanks short, although the northern reefs D do trap some sand.

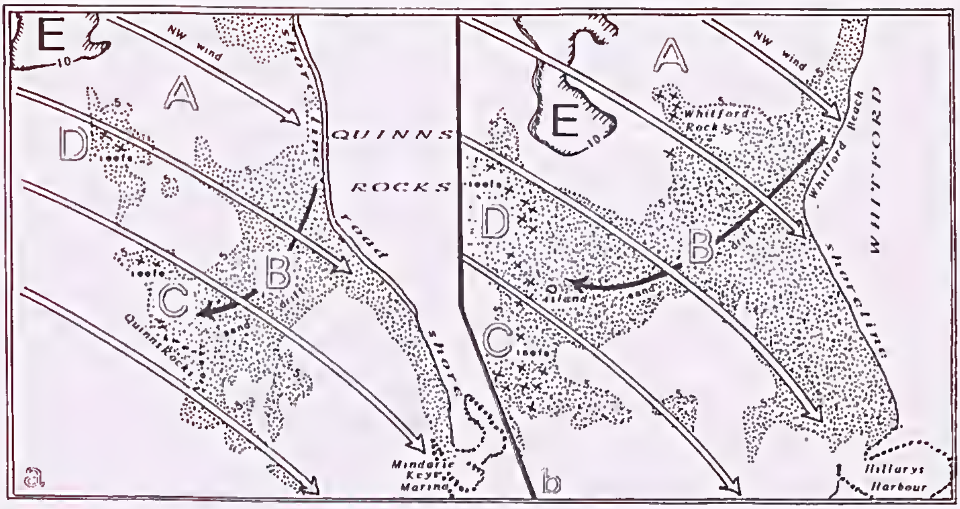

Figure 7. The effect of wind-generated waves on the shore at Quinns Rocks and Whitford Beach. See text for details. *(Base maps by Harbour and Lights Dept).*

Another striking similarity is found in the deeper "pools" at E, where the water is over 10 metres deep. The alignment of these "pools" is a resultant of the NS alignment of the former reefs and the NW alignment of wind and waves.

Needless to say, these complex coastal systems control the habitats of marine and terrestrial littoral organisms.

Exceptionally low water levels during a combination of strong easterly winds, high pressure and low astronomic tides can cause a catastrophic and lethal desiccation of countless molluscs.

CLIMATIC PERIODICITIES AND SINGULARITIES

Much has been written in the past about climatic cycles; the literature to about 1970 was reviewed (Gentilli 1971), but the search for cycles seems to have abated now, to be replaced by an extraordinary interest in El Niño and the Southern Oscillation (ENSO), with Australian implications already ably discussed by O'Mahony (1961). Perth is on the reverse side of Australia and these phenomena are far less significant here. Cycles and long-term trends in them have been sought to some extent, but have not been clearly established because of the paucity of reliable long-term records. The term *cycle* is used more rarely now, after the disappointments experienced with phantom cycles at the beginning of this century. The term *oscillation* is now preferred because it does not imply any cyclical sequence. The term *periodicity* does imply a return after a period, but without great regularity. Perhaps it might be said that 'cycle' implies the possibility of useful forecasting, whereas 'periodicity' means that the event is likely to return after the expected period, but the amplitude of any swing or changes could not be forecast. Modelling is used to forecast changes that may follow given climatic trends or events, but has given conflicting results so far (Henderson-Sellers 1991) and some disagreements between findings as to possible temperature changes near Perth would be quite amusing if they were not taken too seriously by unwary readers.

Diurnal or *circadial* cycles are fundamental in most nature studies, be they of bird song and the hourly and seasonal changes in the dawn chorus, or of mating, brooding or feeding activities. Nocturnal activities should never be neglected, and nocturnal feeding is the main source of energy for many animal species. Figures 3 and 5 may give some useful climatic background.

There is no *weekly* cycle in nature, but in any urban area animal life may be periodically disturbed by human activities, or may conversely be allowed to remain undisturbed on weekends. Noise, smoke and chemical emissions are the main sources of disturbance, with a minimum on weekends and holidays. Road traffic does not disturb coots seasonally feeding near the Stirling Highway exit of the Kwinana Freeway or doves which made occasional news by nesting in traffic lights.

The *lunar* cycle of about 28 days manifests itself in the variation of nocturnal light, felt by some animal species (e.g. magpies which carol very softly by a full moon), and in the *tidal* cycle, which affects the level and in turn the temperature of coastal waters . Some gardeners believe that 'planting by the moon' is effective, but careful experimental observations are needed, and evidence from wild life has not been gathered so far.

The *seasonal* or, more accurately, *annual* cycle is fundamental to organic life. The climate of Perth contains two major annual elements, namely heat, which is the direct result of astronomical factors and therefore follows global principles (apart from the effect of altitude), and rainfall, which is controlled by atmospheric circulation over land and sea, and therefore is strongly affected by local and regional factors. As a combined result and as shown by Table 2 and Figure 4, Perth climate has two opposite extreme seasons, very hot and very dry (*birak* plus *burnuru*, or summer) and very cool and rainy (*makuru* or winter). The intermediate seasons (Figure 4) are characterized by fast rates of change, which bring about a multitude of physiological and behavioural responses from most organisms. Fast as they may be, these seasonal changes are subject to occasional reversals of trend lasting three to six or seven days, the so-called *singularities*, which are caused by atmospheric circulation, particularly by the latitude, size and shape of the great anticyclones that travel from the Indian Ocean to the Pacific, passing nearly always over Perth.

The best known singularities of other continents, such as the 'Indian summer' of North America and the 'sheep cold spells'of Central Europe, may well have their counterparts in Australia , but have not (yet?) got into the folklore. From 35 years of temperature records (Bureau of Meteorology, 1969) we find that March 9 to 11 and 22 to 24 are on the average hotter than the days that precede them, while the general trend at that time of the year is for temperatures to become lower. This might be the counterpart of the North American 'Indian summer'. April 2 to 4, two months before the summer solstice, are often warmer than the six preceding days; this may well be the counterpart of the European 'St Martin's sommer'. From 5 to 8 October the nights are on average colder than theprevious12 nights, which could be Perth's counterpart of Germany's 'sheep cold spells'.

From 85 years of record it results that May 30–31 and June 1 and 2, and June 7 to 10, receive noticeably more rain than the preceding and following days. This is a singularity which is more likely to be due to the passage of moisture-bearing cloud bands (Gentilli 1979b). On the other hand less rainy spells (e.g. June 23–25, July 9–13, July 31 and August 1–2) are more likely the result of persisting anticyclonic regimes when a high is blocked for a few days east of Perth. It must be stressed that, while these singularities leave their mark on long-term averages, they are too unpredictable to be safely forecast.

There are climatic *periodicities* of about two-years' wave length, such as the *quasi-biennial oscillation* (*QBO*) of solar origin, and the *southern oscillation*, expressed by an index (*SOI*) usually based on the difference in atmospheric pressure between Tahiti and Darwin. O'Mahony (1961) found that at Perth there is a strong periodicity of 2.1 years in the August rains. A periodicity of about 2.8 years is noticeable in the March, June and October rains, while in October the period is slightly longer but still under3 years. These quasi-biennial periodicities have also been verified in some coastal processes and should be studied in relation to *biennial rhythms* in the organic world.

A relatively blurred period of about five years has been noticed, which may be half a *sunspot* cycle and/or some interference in successive quasi-biennial 'cycles'. The full sunspot cycle lasts 11 years on the average, but may be as short as eight or as long as twelve years.

Longer periods of about 18 years (Saros cycle, based on lunar nodes) and 35 years (Brückner cycle) have been verified, the former in astronomy, the latter possibly in the deposition of river sediments, but we have no evidence of their effects on organisms, not perhaps individualy, but at least on their abundance.

LONG-TERM TRENDS

The choice of the period over which to verify any long-term trend may be arbitrary and possibly misleading. Statisticians suggest that a reasonable analysis may be obtained from about 30 consecutive items. It was traditional in meteorological and climatological studies to consider the average of 30 years as the 'normal' value of temperature, rainfall, etc. In practice, however, a lot may depend on what years are included, because changes within the 30 years may even themselves out, and on the other hand some very significant changes may happen to occur just outside the chosen 30 years. Most of this study is based on half a century, the 50 years from 1940 to 1989 inclusive.

Figure 8 shows half-century trends in monthly rainfall as straight lines calculated from all the years. In reality of course the actual rainfall in each month may differ wildly from any value shown by the straight line, but the line still remains the simplest, yet quite accurate representation of the 50-year trend, unless one chooses representation by a more or less complicated curve. The calculations and the graph show that June rainfall would have been about 210 mm in 1939 and 165 by 1989, a loss of some 45 mm. July rainfall fell from about 185 to 165 mm, a loss of about 20 mm. This contrasts with earlier findings: between 1877 and 1947 June rainfall had increased an average of 42%, and July rainfall 25% (Gentilli 1952). The contrary trend appeared in January and February rainfall, which had decreased 35% and 41% between 1877 and 1947: these are the only months to show a rainfall increase between 1940 and 1989.

Figure 9 shows the percentage amounts of total yearly rainfall in four different 20-year periods, 1887–1906, 1916–35, 1940–59, and 1968–87. The black squares of 1916–36 are at the right of the graph, showing that every year of that period (except the second-wettest one) had more rain than the corresponding years of the other periods. The small circles of 1968–87 are all to the left (except the lowest one), showing that those 19 years were the driest.

The most extraordinary period was 1940–59 (small triangles) in which occurred both the wettest and the driest years among those shown. Its symbols range from top right to bottom left of the graph, while remaining tightly bunched near the middle. Obviously a period worthy of further study. On the other hand

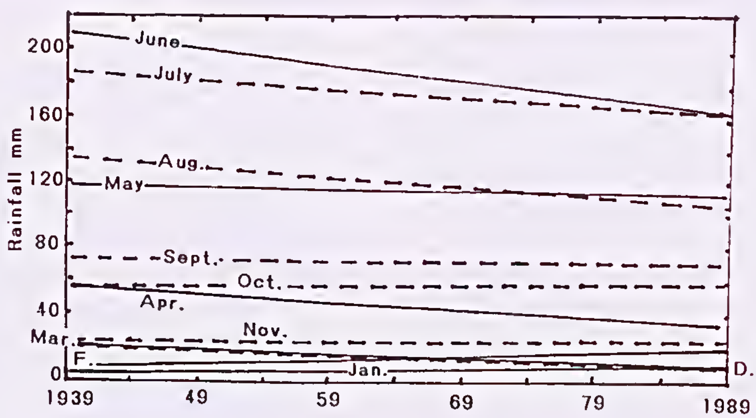

Figure 8. 50-year straight-line trends of Perth monthly rainfall. The lines are calculated taking into account every single month, and so show the true trend; individual months' falls would vary wildly on either side. Winter months have become drier.

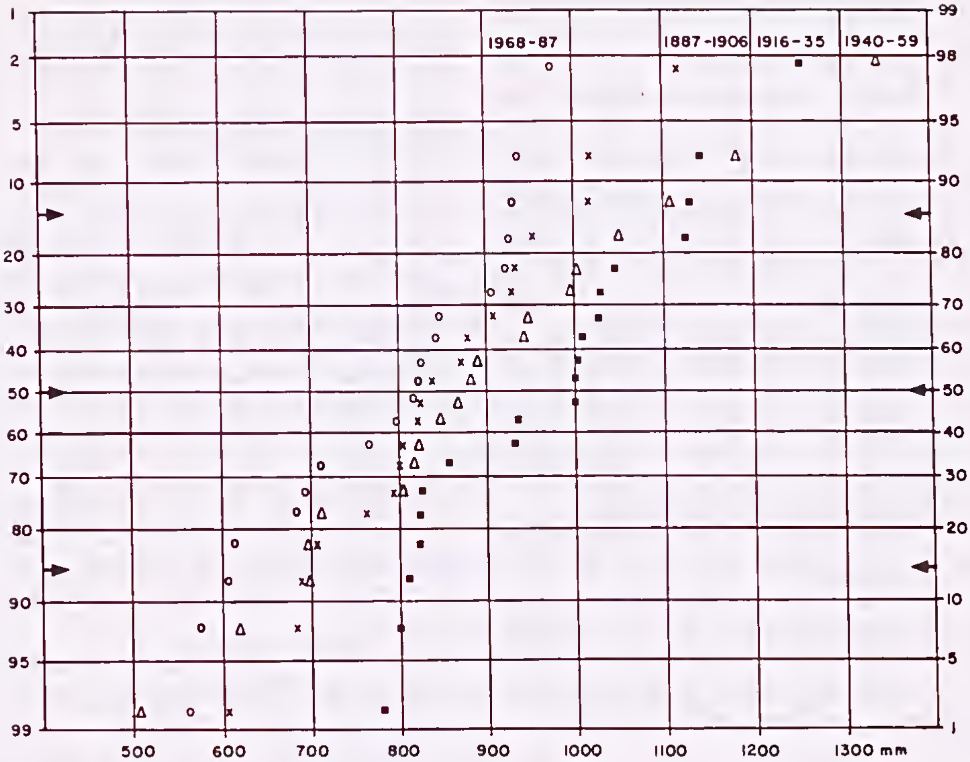

Figure 9. Percentage distribution of the annual rainfall in four 20-year periods (shown at the top with the respective simbols). Rainfall is shown at the bottom, descending and ascending percentages at the sides. 1968–87 (small circles) was driest, 1887–1906 (crosses) second driest, 1940–59 (triangles) second wettest and most uneven, 1916–35 (black squares) wettest and also most even.

1916–35 (black squares) was remarkably even and moderate in the driest third of its years, which all hovered around 800 mm each, not far below the average rainfall. A number of interesting points shown by Figure 4 would have escaped an analysis based on 30-year 'normals'.

CONCLUSION

Naturalists should always refer to standard climatic data as a firm baseline, but should be fully aware of the realities of the microclimates experienced by the subjects of their studies, noting and recording as much as possible and as often as possible. For instance, the speed of movement of most ants near the entrance to their nest seems to vary in some relation to temperature, but is this because of a direct effect of heat on insect metabolism, or is it simply the result of an effort to avoid too much exposure to potentially lethal temperatures, or both? Especially when water is scarce, the actual rainwater reaching the ground, be it in the forest or in the garden, must be measured in order to learn under which true climatic conditions plants and animals live. Measurements of wind speed at different heights can show what kind of windbreak is needed to protect sensitive plants from excessive water losses. Sensitive and accurate instruments, particularly recording ones, may be very expensive, but ingenious improvisation and careful and regular observation may enable naturalists to estimate, understand and to some extent influence climatic environments around them. The time dimension is essential, and short-term and long-term variations must be recorded and taken into account. Climate may be a most important factor in fostering or hindering the life and behaviour of the many fascinating organisms worthy of study and protection.

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